RAILWAY ELECTRIFICATION
25kV a.c. Design on B.R.

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INTRODUCTION

Experience of design, installation and operation of electric traction on the railway network in Britain started over eighty years ago with d.c. conductor rail systems on suburban lines. At that time Great Britain was the first country in the world to be confronted with the problem of very dense traffic in its large towns, resulting in the need to increase the capacity of the existing railways.

After a comprehensive review, in 1956 British Railways decided to adopt a high voltage 50 Hz single-phase overhead line system for all future major electrification projects.

Equipment designs and practices adopted for 25 kV 50 Hz electrification on the BR system are the result of a continuous pattern of development since 1956. This development has allowed modifications to be made in the light of operating experience and advantage to be taken of technological innovations. Great stress is laid upon safety, not only for the public but also for staff operating the system and for others working on or about the electrified railway or on any other equipment located near to the electrified railway.

The dense traffic patterns on the BR network, with mixed types of trains, call for an exceptionally high level of reliability in the traction supply system, to be achieved as economically as possible in first cost and in ongoing maintenance costs.

The power for the 25 kV traction system is obtained from the national electricity supply network. BR does not itself own or operate any generating plant or high voltage transmission system for the purpose of supplying its 25 kV traction network.

1. POWER SYSTEM DESIGN

1.1 Power System Study

The complete power system study for electrification comprises two closely related studies – the "Railway Electrification System Design" and the "High Voltage Transmission System Study."
The railway electrification system design encompasses many aspects of the engineering and operational detail and the prime objective is to produce a 25 kV system design commensurate with the railway commercial service operating standards required and the availability of suitable electricity supplies.

The high voltage transmission system study is an essential part of the programme since it must be shown that the main electrical supply system of the electricity supply authority is not unduly disturbed by the railway loads and that other consumers do not find cause to complain. Also it must be shown that sufficient power is available to obtain satisfactory operation of the railway under normal power system operation and under conditions of one worst case outage at any supply point.

The parameters of design typical for the interface with the high voltage transmission system at the point of common connection with the closest non-railway consumer are:-

(i) **System Voltage Fluctuation**

The voltage changes presented by the traction load to the point of common connection:-

(a) The voltage change caused by load changes with a cyclic variation of greater than two hours is limited to no more than 3%.

(b) The voltage change caused by load changes with cyclic variations of less than two hours but greater than two minutes is limited to a step of 1½% followed by a ramp of 1½% over two seconds.

(ii) **Limits of Unbalance**

The limits used are those given in IEC standard 34-1. (Original Edition).

These state that the limit of negative phase-sequence voltage that can be applied to induction motor terminals is 2% and that a.c. generators must be capable of operating when the circuit supplied absorbs a negative phase-sequence current of not more than 5% of the positive phase-sequence component.

(iii) **Limits of Harmonic Distortion**

The standard normally applied is that the maximum value of voltage distortion due to any harmonic must not exceed 1% and
the total RMS harmonic distortion must not exceed 3%.

1.2 Power Supply System Capacity

In order that the short-circuit capacity of the supply system is sufficiently high for it to absorb the phase unbalance currents and harmonics produced by the single-phase traction loads without exceeding the limiting values of voltage variation, it is normally necessary to make the connections to the supply authorities' networks at 132 kV. Nevertheless the single-phase transformers are connected to different phase pairs of the 132 kV system at the various supply points along the railway so as to provide the 132 kV system with a load that is balanced as far as practicable over the three phases when the traction load is at its highest.

The specification for single-phase transformers stipulates an impedance value to limit the maximum fault current on the 25 kV system to a level which will avoid damage to signalling circuits and limit interference with adjacent electrical circuits and track circuits. For the British Railways network the maximum fault current seen on the 25 kV system is normally 6 kA.

1.3 Incoming Supply Arrangement

The security of the incoming supply is of paramount importance to the reliability of the traction distribution system and normally the incoming feeder circuits from the 132 kV supply network to the 25 kV feeder station are duplicated at each supply point. Both incoming circuits are capable individually of carrying the total load at the incoming supply point for normal traffic operating conditions.

Where practicable the HV feeders from the supply system to the 132/25 kV transformers are derived from a source which has itself a level of security at least equivalent to that afforded by the provision of independent, duplicate, fully rated, incoming feeders to the 25 kV railway distribution system. Such levels of security at the supply point may be provided by an HV busbar, sectionalised by a circuit breaker, with each section of busbar being fed via an independent circuit from an independent part of the HV network or by a duplicate HV busbar with the two busbars being similarly independently fed, such that failure of supplies to one section of the busbar does not interrupt supplies to the other. In such a case the two "railway" feeders would be connected one on each section of the HV busbar but may be "banked" with 132/
33 kV or 132/11 kV transformers feeding local distribution networks or other consumers to economise on 132 kV switchgear, the "bank" being controlled by a single 132 kV circuit breaker (See Figure 1 – Diagram of a typical 132 kV supply arrangement).

The loss of both 25 kV supplies to a feeder station, which may, statistically, occur only once within the life of the equipment, can be catered for by transferring the load on each of the incoming 25 kV feeders to the nearer 25 kV incoming feeder at the adjacent feeder stations. Such a transfer would give rise to some loss of train performance in the affected section since the voltage drop from the feeder station to the pantographs would be higher than under normal feeding conditions due to the increased loadings and the increased 25 kV feeding distances. This loss of performance would be reflected in slightly longer running times for trains passing through the section, but any such lost time should be recovered in the succeeding normally-fed sections with the result that overall journey times are unaffected.

The power supply points for the 25 kV system are required at intervals of between 40 and 60 kilometres and under normal feeding arrangements each one feeds to the mid-points between itself and the adjacent supply points. Further electrical sectioning and paralleling of the overhead line track equipment is provided by track sectioning cabins. A typical arrangement is shown in Figure 2.

For the supplies from the 132 kV system, British Railways has standardised on two sizes of transformer:

10 MVA Oil immersed, naturally cooled which with the addition of oil circulating pumps and forced air cooling have a rating of 14 MVA. This design of transformer, which is used mainly on suburban electrified lines, has a fixed ratio of 132/25 kV.

18 MVA Oil immersed, naturally cooled which with the addition of oil circulating pumps and forced air cooling have a rating of 26.5 MVA. This design of transformer has a variable ratio of 132/25 kV minus 0% plus 12⅞% in 2⅝% steps. On-load tap changing equipment is not provided, the transformer ratio adjustment being achieved by off-circuit selectors. Experience has shown that once adjusted to give the most favourable operating no-load voltage, as determined by the characteristics of the incoming supply voltage, the tapping position is unlikely to be changed.
1.4 Earthing

The earthing of British Railways traction equipment conforms to the recommendations of British Standard Code of Practice C.P. 1013, 1965, the Electricity Council’s Engineering Recommendations S5/1 and the Institution of Electrical Engineers’ Regulations. The key parameter is to hold the potential of exposed metal to a value not exceeding 25 volts under normal operating conditions or 430 volts under traction system fault conditions, measured to the general mass of the earth.

It is normally not necessary to use driven earth rods, as the foundations of the overhead line structures connected in parallel by means of the traction return current rail of the track, keep the earth resistance to an acceptable level. Each overhead line supporting structure is generally directly bonded to the traction return rail of the adjacent track by stranded aluminium conductor sheathed with PVC. As the structure foundations vary in depth from two to three metres, they are little affected by changing weather conditions; the resistance of a single footing does not exceed 20 ohms and is normally much less. When interconnected they provide a very satisfactory distributed earthing system having an overall resistance to earth of 1 ohm or less.

1.5 Suppression of Interference

Railway telecommunications and signal circuits parallel the electric railway throughout its length at close proximity and are therefore exposed

![Diagram](image-url)

**KEY.**
- B/T - Booster Transformer
- I.O.S. - Insulated Overlap Span
to electrical interference from the overhead line traction conductors. British Railways conform to the Directives of the CCITT and, in the design of the fixed traction equipment, booster transformers and return conductors are used to provide as much suppression as is practicable at source. In addition the Telecommunications Engineer takes protective precautions on the communications systems. The normal maximum spacing of the booster transformers is 3 kilometres. (See Figure 3 - Diagram of booster transformer system).

The return conductors are carried on but insulated from the overhead line equipment supporting structures. The booster transformers, which have a 1/1 ratio, force a current through the return conductor equal and opposite to the current in the associated catenary/contact wires. Nevertheless the spacing between the two conductors constitutes an inducing loop which will cause induced current in adjacent conductors and in the traction return rails. This secondary induced rail current, the value of which will be dependent upon rail impedance and rail to earth impedance, will itself have an inducing effect upon adjacent conductors. For some of these adjacent conductors the inducing effect of the ‘loop’ will be dominant, and for others the inducing effect of the rail current, dependent upon the relative physical dispositions of the conductors concerned.

Calculation of induced voltages is an extremely complex operation and computer programs have been developed to assist in this work.

Booster transformers are of simple robust construction and have proved to be very reliable in service. Specifications call for the magnetising currents to be limited, since these represent an imbalance between the primary and secondary currents, not only at the fundamental frequency, but at higher frequencies. Saturation levels for the cores need to be kept well above the maximum peak load current levels since they also produce a primary/secondary imbalance and, for currents above saturation level, will affect the wave shape of the secondary current. Some saturation does occur under fault conditions, particularly for faults near to the incoming supply points.

2. POWER SUPPLY TARIFF ARRANGEMENTS

Electricity for traction on British Railways is purchased from two supply authorities, the Central Electricity Generating Board (CEGB) covering England and Wales and the South of Scotland Electricity Board (SSEB) in Scotland.
The CEGB and SSEB tariffs for traction supplies differ in detail, but have the following common principles:

(i) **Service Charge**

At each supply point the supply authority provides the HV switchgear, the railway supply transformers and the associated metering and protection equipment. The capital cost of this equipment is commuted to an annual service charge.

(ii) **Capacity Charges**

To cover the cost of providing capacity in the generating and HV transmission system the two supply authorities make capacity charges which are related to the total railway demand on the supply authority system at the time(s) of supply system maximum demand(s).

(iii) **Running Charges**

The cost of energy is related to the actual cost of base fuels (coal, oil or nuclear fuel). To assist the supply authority with management of the system load, an incentive to consume energy at times of system minimum demand is given by supply authorities through cheaper off-peak rates.

The overall cost of electricity for traction on British Railways is made up approximately of 2% Service Charge, 25% Capacity Charges and 73% Energy Charges.

3. **25 kV DISTRIBUTION EQUIPMENT**

3.1 **25 kV Switchgear**

The major item of distribution equipment is the 25 kV Switchgear and in the interests of economy in first cost, ease of installation and minimisation of maintenance, switchgear incorporating vacuum interrupters is now standard on British Railways. The vacuum interrupter shows marked improvements over the bulk-oil type circuit breakers previously used, not least in removing entirely the risk of fires and explosions inherent in the presence of quantities of oil. The small contact travel and light weight of moving parts means also that simple, very lightly stressed, operating mechanisms can be used with consequent savings in auxiliary power supplies for operating purposes.
The interrupters themselves are virtually maintenance free, the only routine attention being the cleaning of insulator surfaces and a periodic test for loss of vacuum. Since busbar insulation needs cleaning at the same period as the interrupter insulation a common outage may be utilised for such cleaning, for the vacuum loss test and for testing the integrity of conductor joints. It is not necessary to isolate circuit and busbar components independently and busbar isolating facilities have been dispensed with on incoming and outgoing circuit units. External circuit disconnectors are used to isolate the switchgear from any incoming feeder circuits and from the overhead line equipment, thus obviating the requirement for integral circuit disconnector facilities. Provision is made to enable a faulty interrupter assembly, complete with its operating mechanism, to be removed and replaced by a spare unit, pre-adjusted in the maintenance workshops.

At feeder stations and at mid-point track sectioning cabins, where neutral sections are provided in the overhead catenary/contact system, bus-section circuit breakers are provided in the 25 kV switchgear. These circuit breakers have isolating/earthing facilities on each side and are provided with metal barriers with through bushings. These facilities enable either half of the switchboard to be shut down and the appropriate section of busbar to be earthed with the other half still in full working condition. Maintenance outages can then be arranged with only a minimal amount of emergency feeding even at a feeder station. Similar facilities are not considered necessary at intermediate track sectioning cabins since the external overhead line disconnectors can be arranged to by-pass the switching station when an outage is required for maintenance purposes.

Connections from the switchgear to the overhead catenary system or from the incoming supply transformers are made in bare conductors, through-roof bushings being utilised to take these connections from the inside to the outside of the switchgear enclosure. The bushings themselves provide a convenient location for current transformers for protection purposes, the protection relays being mounted on the front panels of the circuit breaker equipment.

The enclosure for the switchgear is extremely simple, a factory prefabricated modular steel construction being used. By extending the enclosure slightly beyond the circuit breaker equipment, space is provided for ancillary equipment such as tripping batteries, supervisory control equipment cubicles, telephones and the like, enabling inter-
connecting wires to be run directly without recourse to the auxiliary cabling necessitated by separate buildings. The enclosure requires only a simple slab concrete base that can be laid by the same train as is used for concreting the foundations for the overhead equipment structures.

All 25 kV switchgear is, under normal operating conditions, remotely controlled from an electrical control room but provision is made, by means of control changeover switches and local control switches, to enable the circuit breakers to be operated at the switchgear. Where motor-wound spring closing mechanisms are used, facilities are also provided for manual charging and release of the springs and for both spring-closed and solenoid-closed circuit breakers, direct mechanical trip buttons are fitted.

Because the mechanisms have a very low loading, closing coils, closing releases and trip coils have a low auxiliary power demand which can be catered for by simple sealed cell batteries. Spring mechanisms are arranged to recharge automatically after a closing operation, thus ensuring that a further closure can be made even if the auxiliary supply for the spring winding motor is lost. Provision is made to ensure that the supervisory control equipment remains operative in the event of the loss of auxiliary power supplies to enable essential switching operations to be carried out under remote control.

Figures 4 and 5 illustrate respectively the operating corridor and the 25 kV chamber of the 25 kV switchgear and figure 6 shows a vacuum circuit breaker spring operating mechanism with cover removed.

3.2 Protection Equipment

The protective scheme provided for track feeder circuit breakers is a slightly modified version of the static distance-measuring relay scheme which has been used for a number of years to provide high-speed protection for high voltage transmission systems throughout the world. The advantage of this relay is that it can maintain very fast operating speeds and high accuracy of measurement over a very wide range of system conditions. This is of importance on a multi-track railway where it is essential not only to give rapid fault clearance but to prevent the disconnection of supplies to healthy sections of overhead line equipment.
Basically there is a three-zone scheme of distance protection, with Zone 1 providing instantaneous protection for about 80-85% of the protected section, and Zones 2 and 3 providing time-delayed protection for faults in the end of the protected section not covered by Zone 1 and back-up protection for faults in adjacent sections. Static timing circuits are incorporated to provide the necessary time delays.

Use of static protection equipment in conjunction with the vacuum circuit breaker has reduced the total Zone 1 fault clearance time to about 90 milli-seconds, compared with 200 milli-seconds with electromagnetic protection and oil circuit breakers, with consequential reduction in the stresses to which the overhead equipment is subjected under fault conditions.

Protection against very high impedance faults or sustained heavy overloads on track feeder circuits is provided by thermal overcurrent relays. Bus-section units are equipped with overcurrent protection arranged to give an instantaneous trip if closed onto a fault: following a successful closure, the overcurrent protection may then be time delayed to act as a back-up for the track feeder circuits on the same switchboard or, if back-up can be provided adequately by the track feeders at adjacent switching stations, rendered inoperative to avoid mal-discrimination with the track feeder protection. At mid-point track sectioning cabins, relays are provided to sense the voltage on the two sections of busbar and allow closure of the bus-section circuit breaker only when one of the two sections is not energised.

The primary protection scheme on incoming supply circuit breaker(s) at the 25 kV Feeder Stations is co-ordinated with the protection equipment, normally consisting of a form of circulating current or balanced earth fault protection, fitted to the high voltage circuit breaker(s) controlling the supply transformer(s) to cover faults on the transformer(s) or on the high voltage or 25 kV connections to the transformer(s). Additionally, an inverse time definite minimum time over-current relay is provided to cover 25 kV busbar faults, or sustained high overcurrents, and to afford back-up should an outgoing track feeder circuit breaker fail to clear a fault. The trip circuit is monitored continuously to draw attention to any failure of the trip supply or to any break in the tripping circuit.
3.3 Supervisory Control System

With the advent of microprocessor, solid-state supervisory systems the tendency on British Railways has been for electrical control rooms to extend the electrified area supervised and a number of control rooms supervise 1500 single track kilometres of electrified line and are capable of extensions to control at least 3000 single-track kilometres.

The solid-state equipment operates in a continuous scanning mode in which data is continually being transmitted from the control centre to the out-stations and vice versa. Time-division multiplex principles are used whereby all stations in the system are scanned in turn, the scanning mechanism pausing on each station for a short period of a few milliseconds, so that the condition at that switching station can be transmitted to the control centre. If the state of any equipment in that switching station has altered since the previous scan, all circuit breakers and alarm functions are interrogated and the complete information pertaining to the station transmitted to the control centre and indicated on a mimic diagram from which all circuit breakers can be controlled.

The system ensures that the control operator's attention is drawn very rapidly to the operation of any item of equipment not initiated at the control room or to the occurrence of an alarm condition. The computer-based equipments enable all operating events to be automatically logged and recorded on a paper printout.

3.4 Distribution Equipment Maintenance

In developing distribution equipment for traction networks, British Railways' principal objective after ensuring that the prime requirements of safety and reliability have been achieved, is to reduce maintenance and outages of equipment to a minimum. That this has successfully been achieved with the current ranges of equipment adopted for British Railways' projects, where the switching stations have been designed to exploit fully the capabilities of vacuum interrupters, is borne out by experience with the Weaver Junction - Glasgow installations, brought into full commercial service in 1974.

All maintenance of the distribution equipment, including supervisory control, protection and standby signalling supplies on the 450 single-track kilometre section in Scotland is carried out by a total of four staff.
A comparison between the maintenance attention given to switchgear incorporating vacuum interrupters and that to switchgear incorporating oil circuit breakers shows that each oil circuit breaker equipment has received three times as many man-hours attention as the vacuum circuit breaker equivalent. The oil circuit breaker figures include the time spent in the switching stations for changing oil, but exclude any time spent in the handling or treatment of oil outside the switching stations.

It is pertinent to note that, to date, the attention given to switchgear incorporating vacuum interrupters has consisted almost entirely of periodic inspections, carried out by staff during visits to the switching stations for other reasons. The actual amount of work required following these inspections has been negligible.

4. OVERHEAD LINE EQUIPMENT & ELECTRICAL CLEARANCES

4.1 Overhead Line Equipment

4.1.1 Design

The cost of overhead line equipment and provision of electrical clearance on electrification projects forms a significant part of the total investment and therefore considerable effort has been devoted to achieving the maximum economy in the design of the British Railways Mark III ranges of overhead line equipment.

Cost-effective techniques were applied throughout all stages of design of the equipment, with account also taken of the advantages of simplifying the assembly of components to achieve improved productivity of installation work. In addition, account was taken at the design stage of the financial benefits of reducing the total range of components required. The prime objective of the design was to produce an equipment suitable for high speeds with high reliability and requiring a minimum of maintenance, all aspects especially essential for lines with high traffic density and limited opportunity of possessions for maintenance work.

The Mark IIIIB range of equipment provides good current collection for 200 km/h operation. Consequently, in respect of current collection capability, it is not considered necessary to depart from a simple, two-conductor system unless there is a
future requirement for operating speeds significantly above 200 km/h, when the conductor configuration may be dictated by current-carrying capability, rather than the standard of current collection.

Particular features of Mark IIIIB overhead equipment are as follows:

Nominal continuous current rating 600 A.

Copper-equivalent cross-sectional area:

with new contact wire = 150 sq mm
with contact wire worn 33.3% = 110 sq mm

Main conductors:

catenary — 7/3.95 mm with 5 wires Aluminium, 2 wires Aluminium-coated steel on opposite sides of the outer layer. 11 kN tension.

contact wire — 107 sq mm solid, grooved, hard-drawn copper. 11 kN tension.

Apart from the contact wire and fittings connected directly to it, almost all the overhead equipment components are steel or malleable cast-iron galvanised, or of aluminium or stainless steel. These minimise the use of comparatively expensive copper components.

Except in sidings, where fixed termination of conductors is often employed, the equipment is automatically tensioned, usually by weights and pulleys, in order to maintain constant tension within ±1½% in the catenary and contact wire over a temperature range of 56°C. For this temperature range, the maximum tension length into which the equipment can be divided in just under 2 km.

Except in areas of high wind, where lower figures apply, the maximum span length is 73 m on straight track, but this can be extended to 75 m should a subterranean obstruction be discovered during excavation of the mast foundations on site.
Span length is governed mainly by the tensions in the conductors and blow-off due to wind, related to the maximum permissible deviation of the contact wire of 400 mm from the centre of the pantograph, which allows for sway of the locomotive and tolerances on adjustment of the track and overhead equipment.

The majority of insulators employed are of the solid-core porcelain type, or, in main conductors, the porcelain disc type. However, the following insulators based on glass-fibre rods are of interest:-

(a) Silicone rubber-covered glass-fibre rods for in-line insulation where their small diameter is useful in providing greater clearance at overlaps from passing pantographs, and their light weight is also useful in avoiding excessive sag of the catenary.

(b) A larger diameter glass-fibre rod with PTFE or silicone rubber covering, used as an insulated resilient support for the overhead equipment beneath overbridges or in tunnels, allowing the use of reduced electrical clearances due to its consistent and predictable dynamic performance (See Figure 7).
c) Insulators with ceramic beads threaded onto a glass-fibre rod which have inner surfaces vacuum-impregnated with silicone rubber. This type of insulator is designed so that pantographs can run in direct contact with the ceramic beads and, because of its low weight and small diameter, its dynamic performance is similar to that of the length of contact wire which it replaces. Ceramic bead insulators are used for the insulating members of high speed section insulators and neutral sections. In the latter application, two insulators are inserted into the contact wire equidistant about a supporting structure, the short section of wire between them being earthed and the total along-track length of non-energised contact wire being 4.5m.

Apart from a few special varieties, structures comprise masts for cantilevers, each supporting one equipment on single or double track, and masts for multi-track headspans, where two are connected by wires spanning the tracks to support the overhead equipments. They are of plain Universal Column (H section) galvanised steel in a range of 6 sizes between 152 x 152 mm x 23 kg/m and 356 x 368 mm x 129 kg/m. The three smaller sizes are used for cantilever masts and the three larger sizes, either singly or in braced pairs, depending upon the number of overhead equipments to be supported and number of tracks to be spanned, for headspans.

Foundations are generally of the side-bearing, reinforced concrete type, incorporating a soluble core former to provide a hole into which a mast can be inserted and grouted in position.

Gravity slab foundations are used on soft ground and, in hard rock, small concrete foundations are anchored in position by bars fastened into the rock.

See Figure 8 — Cantilever Type Construction

See Figure 9 — Headspan Type Construction
4.1.2 Maintenance

The pantographs on British Railways are fitted with metallised carbon collector strips and latest wear measurements indicate that the life expectancy of the hard-drawn copper contact wire will be about 60 years, even on the high speed, high traffic density routes.

There has been a significant reduction in maintenance requirements with Mark III equipment compared with earlier equipment and insulator cleaning is confined to limited areas of heavy chemical/industrial pollution.

Staffing for overhead line equipment maintenance is now less than one man per ten single-track kilometres.

4.1.3 Installation

The plans, cross-sections, Bill of Quantities and all other documentation required for installation of the overhead line equipment, representing the application of the basic designs to an actual length of railway and known as "Overhead System Design" (OSD), are produced by a specialist BR team.

The cost of producing OSD documentation has been greatly reduced in recent years by computerising the calculations, production of much of the drawings and of the Bill of Quantities. The cost of the overhead line equipment itself has also been reduced by more accurate allocation of structures and foundations to suit the loadings applicable in each case, made possible by the computer.

It is unlikely that significant further economy can be gained from the design of overhead line equipment, but great savings have been made and will continue to be made by careful planning of installation work, timing it so that it follows at a suitable interval behind preliminary work on the track and signalling, as a continuous, mass-production operation.

The plant employed and its method of operation have been developed over the years, so as to carry out the maximum amount of work in the course of a track occupation and also special equipment has been provided and techniques developed to permit the maximum amount of work to be carried out without possession of the track.
4.2 Electrical Clearances

British Railways' electrical clearances were originally based on the UIC recommendation and for 25 kV were 270 mm static clearance and 200 mm passing clearance, requiring a total headroom above kinematic load gauge at a support point of 680 mm. In 1962, following tests and service experience, the statutory clearance requirements on BR were revised and reduced clearances of 200 mm static and 150 mm passing as shown in Figure 10 were introduced for 25 kV operation. These reduced requirements, together with modifications to the design of the overhead equipment, meant that the minimum headroom could be reduced by 175 mm and this significantly reduced the costs of obtaining electrification clearances.

Research and development work had also established that where insufficient headroom is available to allow the normal catenary/contact wire arrangement, a "twin-contact wire" arrangement where the catenary is replaced by contact wire and the two contact wires are supported side-by-side, gave good current collection even with the most restricted clearance arrangement at bridges.
A key factor in perfecting the twin-contact wire arrangement and so reducing the headroom for 25 kV equipment, was the development of large resin-bonded glass-fibre rods with track-resistant surface covering, which provided a flexible and virtually indestructible combined insulator and support for the twin-contact wires.

In 1974, design effort was concentrated on the investigation of possible further reductions in electrical clearance. The objective set was that any improved arrangement must not degrade the surge and 50 Hz voltage withstand levels achieved with the existing arrangements. These levels were found to be governed by the electrical stress between the live end fitting on the equipment support arm and the roof of the bridge or tunnel. This fitting was re-designed to a semi-circular shape, to distribute the electrical stress more evenly, as shown in Figure 7.

It has enabled the clearance above the live end fitting of the support assembly to be reduced to 95 mm static and 70 mm passing. At the same time, the passing clearance from contact wire to kinematic load gauge was reduced to 125 mm. These “Special Reduced Clearance” arrangements, shown in Figure 11, mean that a total of only 375 mm of headroom is required.

<table>
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<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Kinematic Load Gauge - Normal BR Height</td>
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**SPECIAL REDUCED CLEARANCES**

*FIGURE 11*
room is required above kinematic load gauge for 25 kV equipment, an additional 25 mm being allowed for increased uplift of the contact wire at speeds above 60 km/h. Special reduced clearances are adopted in all cases of exceptional difficulty or expense in obtaining greater headroom.

5. CONCLUSIONS

This paper describes briefly the development of system and equipment design for a.c. electrification on BR since its introduction over 25 years ago. Over that period major advances have been made in the application of modern technologies to all the engineering aspects of electrification design so that costs of current schemes are now not only half of those, in real terms, of earlier schemes, but are also amongst the lowest in the world. This achievement has however not been made at the expense of design standards which necessarily remain at a very high level.